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Unclassified Report

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June 30, 1963 10p [ref]

RESEARCH ON SATELLITE ELECTRICAL POWER CONVERSION

SYSTEMS AND CIRCUIT PROTECTION

Fourth Semiannual Status Report

Background

This report is the fourth semiannual status report on research being conducted in the Department of Electrical Engineering at Duke University under Research Grant No. NsG 152-61, Supplement 1-62 from the National Aeronautics and Space Administration. Work on this project began May 29, 1961. The present report concerns the period from May 1, 1962 to May 1, 1963. This research program is presently being extended beyond May 1963 under NsG 152-61, Supplement 2-62.

During the summer months of 1962, six persons were involved in this program on a full-time basis. In addition to the Principal Investigator this number included a graduate Electrical Engineer, a technician-level student assistant, and three persons involved in graduate studies in Electrical Engineering at Duke. Beginning in September and continuing through the academic year, two persons in addition to the Principal Investigator have worked full time on the program. During this interval, one of the persons completed the requirements for the Ph.D. in Electrical Engineering with his dissertation being concerned, primarily, with research which has been performed for NASA under this grant.

Discussion of Research

I. During the six-month interval preceding the period covered by this report, certain new developments relating to improved SCR inverter circuits were reported to NASA as Invention Disclosures, Numbers 276 and 277. These inverter-circuit developments were also the basis for a technical paper, AIEE No. 62-1029, which was presented in June 1962 at the AIEE Summer General Meeting and Conference on Aerospace Transportation held in Denver, Colorado. This paper subsequently was published in the IEEE Transactions, pt. I (Communications and Electronics) January 1963, pp. 429-433. Copies of this paper have previously been submitted to NASA according to the instructions of our grant and copies of this paper also were included as a part of the second semiannual status report submitted by this project.

More recently, i.e. during the early part of the 12 month interval covered by this report, further work has been done in this area. This has resulted in two additional

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invention disclosures, Numbers 668 and 669 entitled "Frequency Controllable Trigger Circuit for Controlled Rectifiers" and "Circuitry for Controlling Transient Voltages and Currents at the Input and Output of Averaging Filters". This work has also resulted in the preparation of a paper, IEEE No. 63-1090, entitled "Regulated D-C to D-C SCR Converter Employing Nonlinear Two-Core Transformer", and this paper is to be presented in June 1963 at the Summer General Meeting of the IEEE in Toronto, Canada. This paper describes an efficient converter in which certain circuit techniques have been introduced which tend to minimize many of the most serious problems normally associated with the use of SCR's in such power converters. Consequently, the overall size, weight, efficiency, and reliability of this converter compare quite favorably with more conventional converters using SCR's. Since SCR's are used as the switching elements, this circuit is well adapted for use at very high power levels. However, as pointed out in the paper, the circuit also retains its favorable characteristics and is attractive for use even at relatively low power levels. The reader is referred to Appendixes A, B, and C for more detailed technical information about this work.

II. In September 1962 the program mentioned in two previous semiannual reports concerning the application of analog computer techniques to the study of spacecraft electrical system protection was discontinued. This study had been in the form of a preliminary investigation, involving approximately six man-months of effort. The purpose of this program was to consider the potential value of the analog computer as a tool for analysis, design, and evaluation in studies concerned with the problems of minimizing the effects upon spacecraft electrical systems of various transient overload conditions, faults, and malfunctions.

As the complexity of spacecraft continues to increase, it becomes increasingly important that the selection of protective measures and the integration of these measures into the electrical system be done from an overall-system viewpoint. Priorities, of course, must be observed and protective actions must be sequenced. However, the design of such a protective system involves not only a knowledge of sub-system priorities and potential fault conditions; it also requires a knowledge of the transient voltages and currents resulting from these fault conditions and of the manner in which these voltage and current transients are propagated through the system. It is in the study of such transient conditions and their effects upon low-thermal-time-constant circuit elements that analog-computer techniques appear to be especially interesting. Such considerations were the motivation for the consideration which has been given to this approach at Duke.

For this evaluation-level program, only existing analog computer facilities in the Department of Electrical Engineering at Duke University were utilized. These facilities were simple and centered around a 40 amplifier computer. Essentially no nonlinear function-generation equipment was available, and multipliers became available too late in the program to be of use.

Two approaches to the simulation problem were considered. In the first approach each subcircuit, e.g. each converter or converter-regulator, would be considered as a functional block on the basis of its electrical transfer functions. Using the transfer functions of the subcircuits, the entire electrical system would then be simulated on a computer, thereby making possible an examination of transient conditions which are intentionally introduced by simulating fault conditions. In the second approach, an effort would be made to simulate as much as possible of each subcircuit. For example, a converter-regulator would not be represented simply by its input-to-output voltage-current relationships but, instead, would be represented by a much more detailed simulation of the actual conversion and regulation processes which take place within the converter-regulator. Such a simulation would provide considerably more detailed information about the stressing of individual system components but would necessitate a much larger computer facility than would the first approach.

Appendix D contains a technical report on simulation efforts undertaken as a part of this program. Considerable attention has been focused on the problem of realistically simulating the behavior of rectangular-hysteresis-loop magnetic cores in power-handling circuits. This problem involves the simulation of highly nonlinear phenomena of the type which are to be expected throughout a spacecraft electrical system. Thus, the problems and complexities involved in attaining a realistic simulation of square-loop cores are illustrative of the type of simulation problems which would be encountered again and again in such a computer study of system protection.

On the basis of the work which has been done, the following observations are made:

(a) The problems of realistically programming on an analog computer the type of solid-state electrical systems commonly used in spacecraft are made considerably more complex by the highly nonlinear nature of the various system elements. These nonlinearities represent particularly significant obstacles when it is desired to program the functioning of individual subcircuits. (See Appendix D). Consequently, it appears that such a study, to be meaningful, would require a rather large analog-computer facility in which was included adequate accessory equipment for the simulation of various nonlinear functions and effects. Such a study would also require a considerable man-hour investment.

(b) Because of the necessary size of the computer facility and of the scope of such a project as regards the professional man-hours which would be required, it is recommended that, in the event such a protection study is utilized, it be performed at the time of and as a part of the initial system design. By so doing, the computer possibly could be made to provide data which would facilitate the electrical design of the system, which would serve as a guide for the selection of compatible protective measures, and which would provide a basis for the effective integration of these measures into the system. Many problems of design and system protection would be related. For example, the problems of cross-talk between various loads and transient progations through the system due to faults might be found to be quite closely related. Protective considerations would become, from the outset, and integral part of the overall system design.

As mentioned previously, the attention given to this problem has been limited to a brief preliminary examination of some of the potential possibilities and some of the difficulties associated with such an approach to the problems of system protection. Barring specific indications of interest on the part of NASA, it is not now planned that the work along these lines be carried any further.

III. Under contract NAS 5-1980 from NASA, some work has previously been done by members of this research group on non-dissipative converter-regulators incorporating short-circuit protection. This program ended July, 1962. However, at the conclusion of this contract, the interest of the participants in some of the new circuit ideas then being explored was high, and for a time further work along these lines was continued under the present grant.

The results of these explorations are summarized in a technical paper which is included as Appendix E of this report. This technical paper was presented in Washington, D. C. in April, 1963 at the International Conference on Nonlinear Magnetics (Intermag) and was published as a part of the Proceedings of that conference. This paper has also been reviewed and accepted for publication in the Transactions of the Institute of Electrical and Electronic Engineers although actual publication has not yet occurred.

As explained in the paper, Appendix E, these circuits make use of multiple cores within the same transformer package to simulate a saturable transformer with an apparently controllable volt-second capacity. It is shown that the characteristics thus obtainable find direct application in frequency-controllable magnetically-coupled transistor inverters. Such circuits are of interest in regard to both power conversion and information processing. Additional uses of these principles are also pointed out, e.g. the use of these principles in circuits to sum a plurality of d-c input voltages having either common or isolated grounds.

In discussing these multiple-core circuits, emphasis is directed primarily toward the principles involved and the possibilities offered by such circuits, rather than toward special adaptations of the circuitry to specific applications. Experimental results obtained from test circuits are also presented.

Appendix F refers to an invention disclosure concerning this work which has previously been submitted to NASA.

IV. The characteristics of switching transistors and silicon controlled rectifiers are constantly being improved with the result that these devices can now perform efficiently as switches in relatively high frequency applications. This fact, along with the availability of high quality tape-wound toroidal cores suitable for use at very high frequencies, has led to the use of relatively high switching frequencies in d-c to d-c conversion circuitry. SCR converters are frequently operated in the range of 3 KC and transistor converters are often designed for considerably higher frequencies.

Aside from efficiency considerations, few if any real complications result from attempting to operate the inverter stage of a d-c to d-c converter at high frequencies. Significant reduction in the necessary size and weight of the magnetic components of such converters has therefore resulted.

However, it is considerably more difficult to take advantage of the potentially high switching speeds of transistors and SCR's in applications requiring the conversion of direct current to low frequency (60 or 400 cps) alternating current. Here, it is most convenient to perform the inversion by a switching process which has a frequency corresponding to the desired output frequency. Typically the output thus obtained will be a square wave or a quasi-square wave which will have to be filtered for those applications requiring a sinusoidal a-c voltage. Both the low-frequency inverter and the associated filter represent considerable size and weight.

Appendix G concerns some work which has been done under this grant with the objective of enabling d-c power to be converted to a-c power with conversion equipment whose weight and size is consistent with the minimums established by the quality of the available magnetic and switching elements rather than being dictated by the necessity of having a low frequency output. This can be accomplished by synthesizing a low frequency waveform of approximately sinusoidal waveshape from the outputs of one or more high frequency voltage-transformation units. In theory, such an approach is entirely feasible. In practice, it is found that avoiding undue complexity and resulting reliability compromises is a severe challenge. The necessity for providing for the handling of reactive currents in such a system is the source of many of the complications.

Technical discussions of initial investigations relating to this general problem are to be found in Appendix G.

V. As a result of the continuing rapid progress in the development of new sources of electrical energy, there is an ever continuing need for a paralleling development of suitable power converters and regulators to be used with these new sources. Most of these newer sources of electrical energy are characterized by an inherently low-voltage, direct-current output. Weight, size,,and reliability problems are encountered in placing a great many of these low voltage generators in series. The alternative, therefore, is to design electrical-to-electrical conversion units which will accept the energy from these very-low-voltage, high-current sources and efficiently convert this energy to the various voltage and current levels which are required in a given spacecraft.

This particular problem, i.e. the problem of low-voltage conversion, has received considerable attention at Duke during the preceding 12 months. Work has been done on two approaches to the problem.

Effort on the low-voltage conversion problem unavoidably centers around the converter switching elements. Any workable converter design must necessarily make use of one or more switching elements (see Appendix J), and these switching elements must be capable of efficiently switching the relatively large currents to be expected from a low-voltage source of electrical energy. Furthermore, in order to realize a reasonable overall size and weight for the converter, the switching elements must be capable of reasonably high speed operation.

(a) One approach to the low voltage converter problem at Duke has centered about the development of an electrically controllable liquid-metal switch. The basic principles involved in the operation of such a switch were explained in NASA Patent Disclosure No. 487 which was submitted to NASA June 29, 1962. Copies of this disclosure were also made a part of the second semiannual status report from this project.

With the liquid-metal switch, a small quantity of a liquid metal, e.g. mercury, is enclosed within a small container of predetermined shape in which are placed suitable contact electrodes. The ionization potential of mercury is never exceeded in this low voltage application and, therefore, by periodically changing the position of the mercury with relation to the contact electrodes the device may be made to serve as a very effective low-voltage, high-current switch. As explained in the invention disclosure, electromagnetic rather than gravitational or inertial forces are utilized to cause the desired movements of the mercury. Thus, the switch would be well suited for operation in a "weightless" environment and would not depend for its operation on mechanical movements of the container or its supporting members.

This liquid-switch investigation is necessarily very basic in nature and therefore the outcome of this program is very difficult to predict. What is hoped for is a highly efficient switching element, the reliability of which will be compatible with the demands of spacecraft usage. Encouragement is to be found in the fact that such a switch would make possible an all metallic primary converter circuit. The semiconductor materials used in a transistor switch would be characterized by a carrier density on the order of 10^{19} carriers/cm^3 whereas mercury used in a liquid-metal switch would offer a carrier density on the order of 10^{22} carriers/cm^3. Likewise the high boiling point of mercury (356°C) would seem to indicate that, potentially, rather high temperature operation might be feasible with such a switch. Another attractive possibility would be that of being able to operate converters using such switches in a very high radiation environment, e.g. in close proximity to a nuclear reactor. Finally, there is the possibility that such liquid-metal switches could ultimately be fabricated more economically than transistor switches of equivalent ratings. If this be the case, commercial application of these switches could result, e.g. in conjunction with commercial applications of fuel cells.

On the more realistic side of the picture, however, there are many unknowns. Several preliminary test-switches have been built and operated. However, these were relatively low current units and, to an objectionable degree, subject to inertial effects. Long-term reliability is still an unknown factor. In this regard, many problems of materials and construction must be dealt with. Both two-and-four-terminal switches are being studied and considerable attention is being directed toward a switch and converter combination that will not be characterized by an objectionable weight and size for a given power level.

To date, the effort on this liquid-metal switch has been in the form of an initial study of some of the inherent problems. Beginning June 1, 1963 it is planned that considerably more emphasis be placed on this switch.

(b) Other work at Duke on the low-voltage converter has involved the use of transistors as the switching elements. Several companies have developed special transistors for this purpose. However, conventional transistorized inverter circuits fail to take full advantage of the potential efficiency of these transistors, and it is in the development of improved inverter circuitry that attention at Duke has been focused.

This work has been summarized technically in Appendix H and will not be further reviewed here. Appendix H is a copy of a technical paper concerning this work. This paper has been accepted for publication in the Transactions of the Institute of Electrical and Electronic Engineers and for presentation at the National Electronics Conference in Chicago, Ill. in October, 1963. Appendix I refers to an invention disclosure concerning this work which has previously been made to NASA in accordance with the instructions in the grant.

VI. As mentioned previously, one of the persons working under this grant completed the requirements for the Ph.D. degree in Electrical Engineering in May, 1963. His dissertation was concerned, primarily, with research which has been performed under the present research grant from NASA. Appendix J is a copy of this dissertation.

Insofar as technical content is concerned, the readers of this report may conserve time by noting the parallel between Appendixes A and H of this report and Chapters IV and V of the dissertation. Pages 40-43 of Chapter IV present information not contained in Appendix A. Otherwise Chapters IV and V of Appendix J are equivalent technically to Appendixes A and H.

Chapter II of Appendix J is concerned with certain theoretical limitations on electrical-to-electrical energy conversion from direct-current sources. To anyone working with the various concepts and approaches associated with the design of voltage converters, including systems for inversion and regulation, certain general "truths" or rules of the game make themselves felt. Often, however, these fundamental principles are recognized only in a semi-intuitive manner and make themselves felt only in the success or failure of such an effort. It is the purpose of the discussion of this chapter to state certain of these "truths" as rules without formal proof. Though these rules point out the futility of certain approaches to conversion and regulation problems, the primary purpose for stating them was simply to define certain necessary characteristics of physically realizable conversion and regulation systems and to provide useful guidelines for further research. If these necessary characteristics, or ingredients, are recognized in their most elementary forms, perhaps this will facilitate efforts to evolve systems having, for example, less size, weight, or power loss than are characteristic of presently used systems.

Preceding the Appendixes is a statement of expenditures for this project from June 1, 1962 through May 31, 1963.

The participants in this research program would like to take this opportunity to acknowledge and express their gratitude for the invaluable technical advice and information gained through close communication with the Power Sources Section, Spacecraft Technology Division, Goddard Space Flight Center. Particularly profitable have been the several trips to GSFC

by Duke research personnel and the visits to Duke by Mr. E. Pasciutti, Mr. L. Veillette, Mr. M. Davis, and Mr. L. Williams, and by Mr. Fred C. Yagerhofer, Head of the Power Sources Section.